Seismic Analysis of Cable Stayed Bridge Towers with Shape Memory Alloy Anchor Bolts

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1. INTRODUCTION

The anchor bolts are mostly used for column bases in steel cable-stayed bridge structures. Many anchor bolts failures in steel column bases were found in the Hyogoken-Nanbu earthquake 1995 in Japan where anchor bolts has been fractured or pulled out of the base plate. Column base and anchor bolts behavior have a strong effect on the overall behavior of the steel frames, hence improvement of the anchor bolts behavior in the column base connections is most important, and so a more attention should be paid to the proper modeling and the right construction[1)]

Shape memory alloy (SMA) has the unique ability to withstand large strain demands but recover residual strains when reloaded[2)]. When SMA is integrated into a steel connection, they offer the possibility of significantly enhancing the ductility and damping capacity of base connections. In addition, the unique shape memory behavior provides the possibility of removing the residual deformation within the connection by reloading the SMA following a seismic event.

The objective of this study is to investigate the seismic response of steel tower of cable-stayed bridges using a proposed SMA anchorage system. The base connection is idealized by a spring system. A finite element methodology based on theoretical approach and computer simulations for nonlinear dynamic analysis problem including base connection modeling is presented. The effectiveness of the proposed SMA anchor connection in the bridge tower is assessed comparing with the ordinary steel anchor connection by subjecting a cable-stayed bridge tower to strong ground motion and the results are analyzed.

2. SHAPE MEMORY ALLOY (SMA)

SMA is a class of alloys that display several unique characteristics, including shape memory effects, pseudoelasticity, and high damping characteristics. **Figure 1** shows the stress–strain loop of a superelastic SMA material undergoing a stress-induced transformation of SMA at constant temperature. Before the stress reaches a critical value, the SMA behaves elastically. The stress induced martensite transformation takes place and results in a large deformation with little increase of stress. Because of the stress–strain hysteresis, which is identified with the stress difference of the loading and unloading, the area enclosed by the loop represents the energy dissipated through the loading–unloading cycle. Hence, The SMA is characterized by a unique superelastic behavior, which allows the alloy to recover its unreformed shape once the mechanical stress is removed[3)].

During an earthquake event, connectors in various structures are prone to damage. SMA connectors have been designed to provide damping and tolerate relatively large deformations. Tamai and Kitagawa[4)] proposed an exposed type column base with SMA anchorage for seismic resistance.

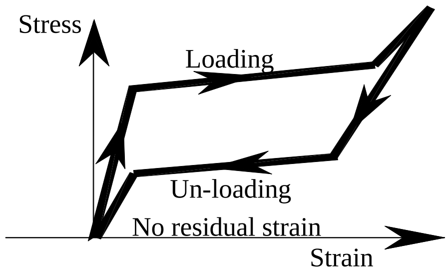

Fig. 1 Stress-strain relationship for SMA

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3. ANALYSIS AND METHODOLOGY

Based on the total incremental equilibrium equations, large displacement 3D beam-column element formulation is carried out. The implicit Newmark's step-by-step integration method is used to directly integrate the equation of motion and then it is solved for the incremental displacement using the Newton Raphson iteration method where the stiffness matrix is updated at each increment to consider the geometrical and material nonlinearities and to speed the convergence rate. In addition, the tower structures damping mechanism is adapted to the viscous damping of Rayleigh's damping type with damping coefficient to the in-plane and out-plane fundamental natural vibration modes equal to 2% for steel material of tower superstructure.

The steel tower of Tappu cable-stayed bridge located in Hokkaido, Japan is considered. The steel tower is taken out of the cable-stayed bridge and modeled as three-dimensional frame structure characterized by a fiber flexural element. The tangent stiffness considers the material nonlinearities through elastic-plastic constitutive model incorporating an unaxial yield surface criteria and kinematic strain hardening flow rule. The steel yield stress and modulus of elasticity are equal to 353 MPa and 200 GPa, respectively; the plastic region strain hardening is 0.01. The geometry of the steel tower and finite element structural model are shown in **Fig. 2**.

For the steel cable stayed bridges, the towers are usually fixed by multiple bolts to large anchor frame embedded in a concrete footing. **Figure 3** shows a sketch of tower base connection design drawings and the frame anchorage system, which provides a reliable and durable anchorage system. A component spring model for base connections is proposed. This model incorporates deformations from tension bolt elongation, bending of base plate and concrete bearing underneath base plates. In order to distinguish between the ordinary steel anchor bolts and the proposed SMA anchor bolts, **Fig. 4** shows schematic details of the ordinary and SMA anchor as well. For more economic, the proposed SMA anchor bolt consists of two parts, the upper part is NiTi SMA material rod while the lower part is ordinary steel rod.

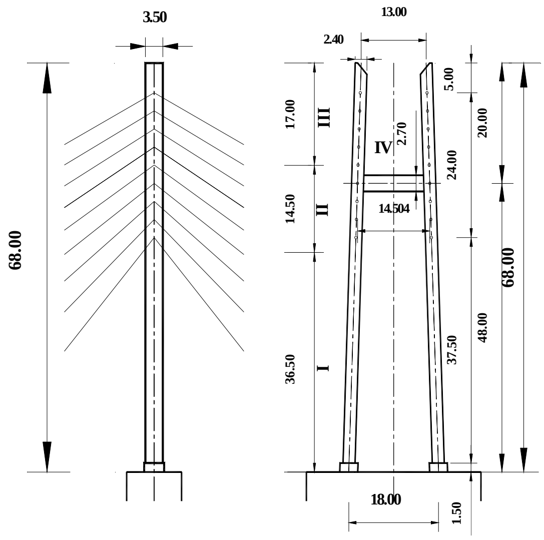

Fig. 2 Steel tower of cable-stayed bridge

The individual components of the connection are modeled by a nonlinear springs. **Figure 5** shows the mechanical model of the base connection. The components of the base connection are represented by a spring system that includes extensional springs to simulate the anchor bolt tension deformation and extensional springs to simulate the concrete in compression under the base plate. Each of these springs is characterized by its own deformability curve as an individual component, as shown in **Fig. 6**. For the steel anchor, it is modeled as bilinear model with initial pretension force while for the SMA anchor bolt, it is modeled to represent the shape memory effect property of the SMA material and its zero residual strain after unloading. Also the proposed SMA model shows the strain hardening property at strain 6-8%. The stiffness and resistance properties of the springs are calculated on the basis of the geometrical characteristics and the mechanical properties of the nonlinear constitutive material as given in **Table 1**. The anchor bolt pretension force and concrete compression pre-stress state as a result of self-equilibrium are considered. The steel bolt plays little part in the compressive behavior of concrete, thus the bolts in compression are replaced by concrete in the finite element analysis. The base plate is assumed rigid ($EI = \infty$) within tower leg dimensions, while the plate projections rigidity (EI) beyond the tower leg is computed.

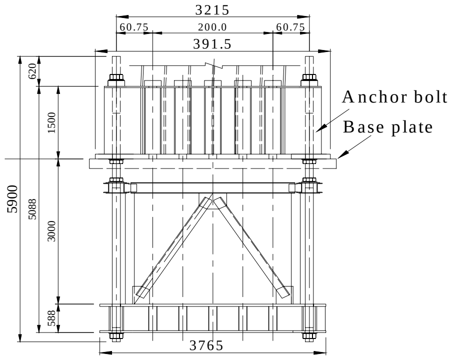

Fig. 3 Steel tower base connection (mm)

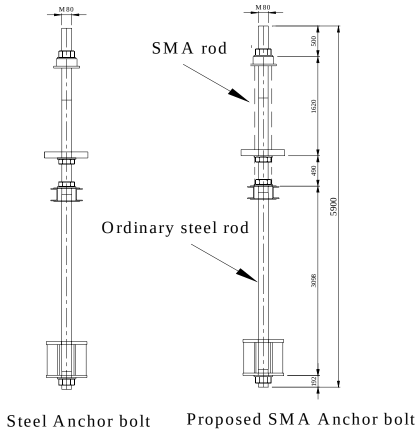

Fig. 4 Steel and proposed SMA anchor bolts

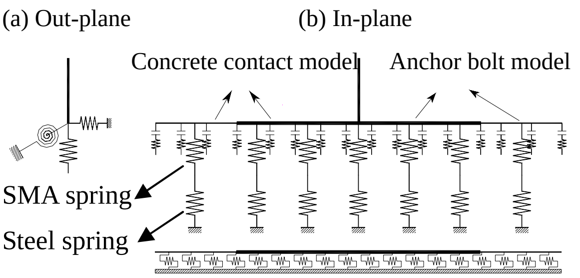

Fig. 5 Tower base connection mechanical model

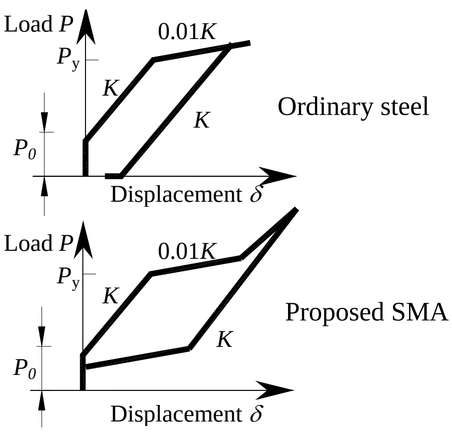

Fig. 6 Anchor bolts constitutive models

Table 1 Base connection components properties

Description	Properties value	
Steel anchor bolt	Stiffness K	201.2 MN/m
	Yield force P_y	1.93 MN
	Pre-tension force P_0	0.81 MN
	Steel	S45C
SMA anchor bolt	Stiffness K	201.2 MN/m
	Yield force P_y	1.2 MN
	Pre-tension force P_0	0.81 MN
	SMA	NiTi

4. NUMERICAL RESULTS

In order to enhance the base anchorage connection, the steel anchor bolts are supposed to be replaced by the proposed shape memory alloy anchors. To evaluate the effectiveness of the SMA anchorage system, the tower is subjected to seismic loads. A finite element analysis of steel towers taking into account the proposed shape memory alloy anchorage system is carried out (case2). Additionally, a comparison to the ordinary steel anchorage system (case1) is presented.

Figure 7 shows the response history of the displacement at the tower top for the bridge subjected to the Hyogoken-Nanbu ground motion record. The maximum displacement of approximately 86 cm occurs in the as-built bridge. The use of SMA anchor bolts for the tower base connection reduces the maximum displacement to 76 cm, a reduction of 12% of the original displacement.

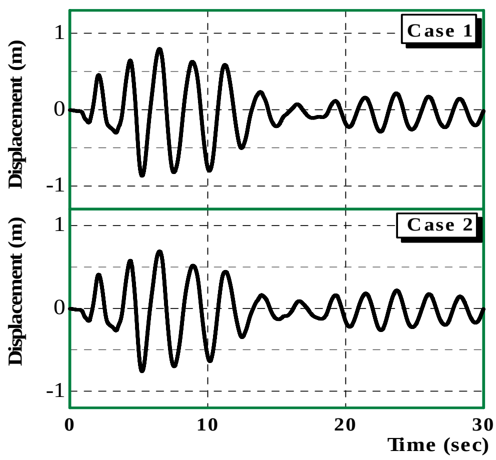

Fig. 7 Displacement time history at tower top

The effect of shape memory alloy anchor bolts is also observed in the force-deformation plot of the anchor bolts shown in **Fig. 8**. In contrast to the ordinary steel anchor bolts, the SMA anchor bolts are effective for repeated cycles. Although the SMA anchor bolts are subjected to a maximum deformation of 14 mm at approximately six seconds in the response, the SMA anchor bolts remain effective for repeated cycles without any strain hardening because the strain didn't reach the percentage required for hardening, 6-8%.

The SMA anchor bolts are effective in limiting the response of the bridge tower because of the energy dissipated by the SMA anchor bolts. A comparison of the energy dissipated by the SMA anchor bolts and the ordinary steel anchor bolts, represented by the area enclosed by the force-deformation relationship, shows the SMA anchor bolts dissipated more energy than the ordinary steel anchor bolts. This indicates that the effectiveness of the SMA anchor bolts comes primarily from its ability to remain elastic over repeated loading cycles. The total input energy is defined as the total energy related to inertia forces induced by the ground motion. It is appeared, as shown in **Fig. 9,** that the proposed SMA anchorage system provided great effects on the tower response that is to its ability to dissipate a large amount of energy input to the tower, resulting in an increase the ability of tower structural system to reflect a portion of earthquake input energy.

5. CONCLUSIONS

A numerical study of the steel tower cable-stayed bridge has been conducted to investigate the efficiency of the shape memory alloy anchor bolts in order to enhance the seismic behavior of cable stayed bridge. A proposed anchorage system of the bridge tower is presented with a numerical modeling of the new shape memory alloy. From this study, it can be concluded that the shape memory alloy is more effective in enhancement of the tower responses and effective in dissipating energy and reducing the total input energy of the whole towers under severe seismic ground motion range in comparison with ordinary steel anchor bolts.

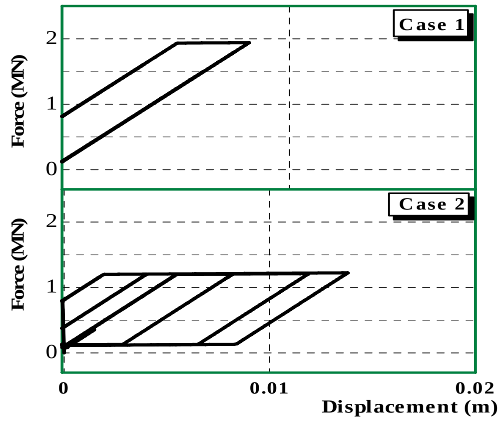

Fig. 8 Force-displacement relationship

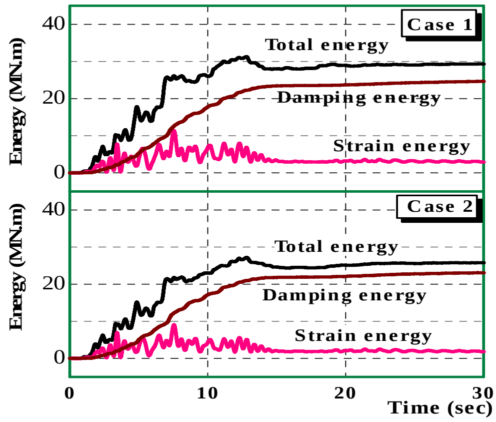

Fig. 9 Total input energy time history of the whole tower

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